3-D Thermal and Seismic Structure of Slab and Plate Interface in Northern Cascadia

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K. Wang, G.C. Rogers, H. Dragert
Pacific Geoscience Centre, Geological Survey of Canada
9860 W Saanich Rd, Sidney, B. C., Canada V8L 4B2

Phone: (250)363-6429; Fax: (250)363-6565; Email: Kwang@nrcan.gc.ca

URL: http://www.pgc.nrcan.gc.ca

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Investigations undertaken

(1) 2-D and 3-D modeling of mantle wedge flow and thermal structure for Cascadia. (2) 3-D seismic tomography for northern Cascadia using earthquake and controlled-source data. (3) Mechanics of earthquakes in warm slabs: comparison of Cascadia and Nankai subduction zones.

Results

1. Thermal modeling

Thermal models provide information on the metamorphic conditions for the subducting slab and how slab dehydration may facilitate in-slab earthquakes. Two important constraints for regional-scale subduction zone thermal models are (1) a temperature as high as 1200-1300ºC in the mantle wedge beneath the volcanic arc, and (2) high heat flow and thus mantle temperatures throughout the backarc region. Using 2-D finite element models, we have investigated the heat budget at a subduction zone and examine the thermal consequences of mantle flow induced by traction along the top of the subducting plate (Currie et al., 2004). An isoviscous wedge does not transport a sufficient heat into the wedge corner. A stress- and temperature-dependent wedge rheology allows rapid flow upward toward the wedge corner and enhanced temperatures below the arc, but it also leads to heat flows that are much lower than

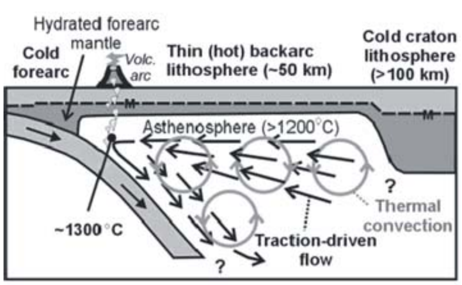

Figure 1. Conceptual model of subduction zone mantle flow. Flow near the volcanic arc is primarily slab-driven. Small-scale free convection occurs in the backarc.

observed. We propose that slab-driven wedge flow is predominant in the forearc and a region of the back arc near the volcanic front while small-scale free convection in a low-viscosity mantle is necessary to maintain a hot back arc (Figure 1). In 3-D models, we focus on the effect of slab driven wedge flow near the volcanic arc and will investigate effects of along-strike variations in the age and dip of the slab and oblique subduction. 27-node bi-quadratic elements are used for the velocity and temperature fields, and 8-node bi-linear elements are used for the pressure field. We have developed a 3-D code for a massively parallel computing environment. Figure 2 shows the result of a simple test. A model for northern Cascadia is being constructed.

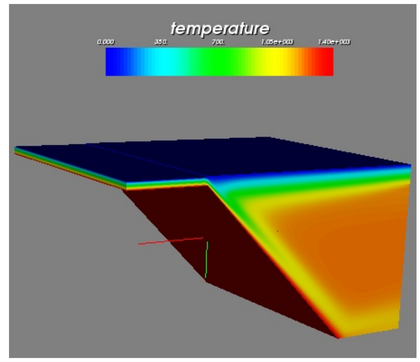

Figure 2. A simple 3-D model assuming slab-driven Newtonian wedge flow.

2. Tomography

A large-scale 3-D P-wave velocity model (Figures 3 and 4) is constructed for SW British Columbia and NW Washington through joint tomographic inversion of first-arrival times from active source experiments together with earthquake travel-time data recorded at permanent stations (Ramachandran et al., manuscript in preparation). Approximately 150,000 first-arrival times recorded at 225 temporary stations from the 1998 Seismic Hazards Investigation in Puget Sound (SHIPS) experiment, and 60,000 first-arrival times from 3000 earthquakes recorded at 91 permanent recording stations were inverted for a minimum structure velocity model. The RMS residuals for the initial and final models are 764 and 132 ms, respectively, which represents a 97% variance reduction. Checkerboard resolution tests indicate a horizontal resolution of 30 km down to 20 km depth, and 50 km down to 60 km depth. The velocity model images the velocity structure of the forearc crust and upper mantle. The geometry of the subducting Juan de Fuca slab is delineated in the velocity model. The velocity model also outlines the structure of the sedimentary basins in the Straits of Georgia and Juan de Fuca, and the Puget Sound region. The mafic Eocene Crescent terrane (Metchosin Igneous Complex in southern Vancouver Island) dips beneath the margin to at least 20 km depth. This terrane is regionally extensive beneath the Strait of Juan de Fuca and the Puget Sound region, with higher than average velocities of 6.8-7.2 km/s, at approximately 15 km depth. In the Olympic peninsula, the Core rocks (accretionary sedimentary prism) are imaged to under-thrust the Crescent Terrane to a depth of at least 30 km. At this location most seismicity is observed to be associated with the overlying high velocity Crescent terrane; the under-thrusting Core rocks are inferred to be aseismic. Beneath southern Vancouver Island, the subduction thrust zone above the Juan de Fuca plate is characterized by low velocities of 6.4-6.6 km/s at 25-35 km depth. Such relative low velocities may be due to trapped fluids, sheared lower crustal rocks, and possibly underthrust accretionary sedimentary or metamorphic rocks. This low velocity region coincides with the high conductivity region mapped in previous magneto-telluric studies, with a dipping band of seismic reflectors, and is devoid of seismicity. Low velocities of 7.2-7.6 km/s are observed in the forearc upper mantle beneath the Strait of Georgia and Puget Sound. Such low upper mantle velocities are inferred to be due to regional serpentinization of cool forearc mantle peridotite by fluids rising from the dehydrating Juan de Fuca slab. The Tertiary sedimentary basins in the Strait of Georgia and Puget lowland lie directly above the zone of forearc upper mantle serpentinization. In contrast, the sedimentary basins in the Strait of Juan de Fuca lie in a synclinal depression in the Crescent volcanic terrane.

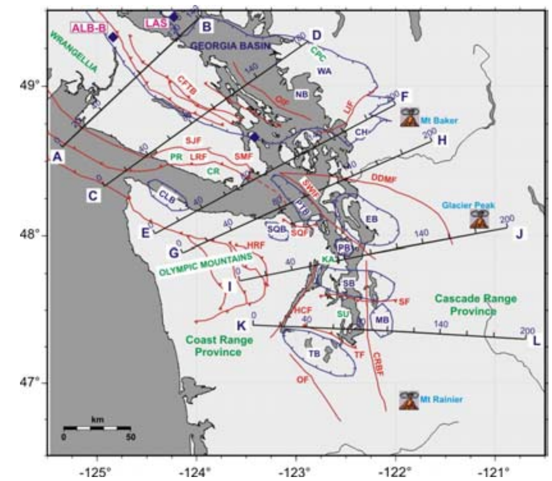

Figure 3. Profile locations for the cross sections shown in Figure 2. Red lines indicate major faults. ALB-B and LAS are seismic stations where receiver function studies have been carried out previously.

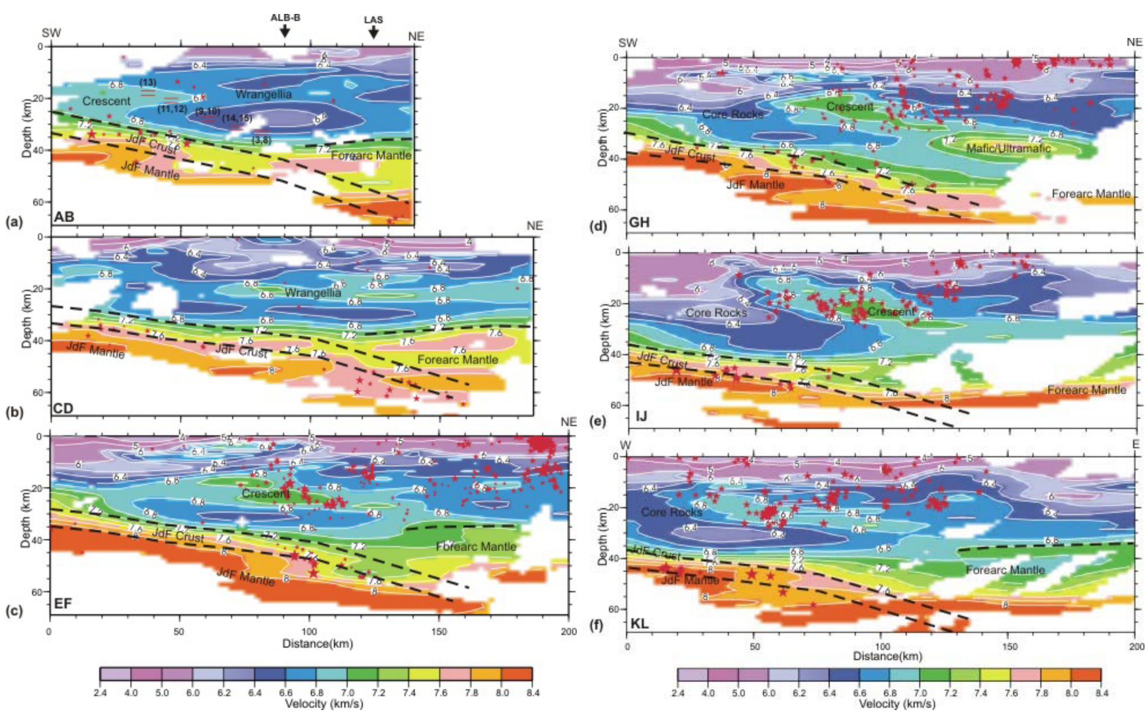

Figure 4. Cross-section view of P-wave velocities determined from tomographic inversion. Profile locations are shown in Figure 3.

3. Slab mechanics

We have inverted focal mechanism solutions to infer stresses in the subducting slab beneath Southwest Japan. We propose that the margin-parallel component of mantle resistance to the obliquely subducting young slab at Nankai provides an easterly stretch, acting against the westerly slab-pull of the older and colder part of the slab at northern Kyushu. Despite the complex slab geometry along the Nankai margin, the direction of tension is largely parallel with the local strike of the slab, indicating that the slab is a stress guide. The maximum margin-parallel stretch and a sharp bending of the slab both occur in the area of the 2001 M = 6.7 Geiyo earthquake. Through synthesizing stress, structural, thermal observations, we propose the slab model for a warm slab shown in Figure 5 (Wang et al., 2004b). We think that crustal densification has shattered the top part of the crust at Nankai, perhaps causing many very small earthquakes and seismic tremors. Larger events that have been used to derive focal mechanisms occur in the untransformed lower crust and the mantle. These earthquakes are driven by tectonic forces, particularly the E-W stretch, but seismic faulting is facilitated by locally elevated fluid pressure due to dehydration of altered parts of the untransformed crust and serpentinized parts of the mantle.

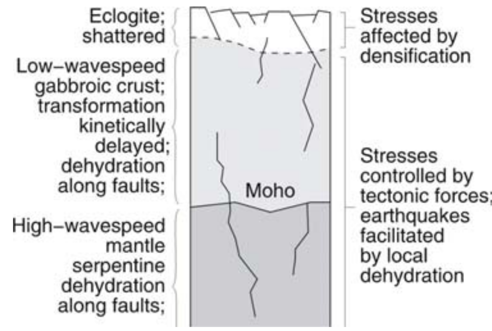

Figure 5. Metamorphic dehydration state of a warm slab slab in the 30-60 km depth range. The untransformed lower crust and mantle have a similar state of stress. From Wang et al. (2004a).

Non-technical Summary

This project is designed to investigate what controls the damaging earthquakes within the subducting Juan de Fuca plate beneath the Pacific Northwest. Thermally controlled metamorphic processes as well as tectonic stresses are considered responsible for the generation of these earthquakes. To have a better understanding of the thermo-petrological process, we are developing 3-D tomography models using both local and remote earthquakes to constrain the rock properties in and around the slab and numerical models to understand the 3-D thermal field. We also explore the implication of episodic tremors and slips in the subduction zone on slab processes and compare the thermal and stress fields with the similar Nankai subduction zone in SW Japan.

Reports Published

Currie, C. A., K. Wang, R.D. Hyndman, and J. He, The thermal effects of slab-driven mantle flow above a subducting plate: The Cascadia subduction zone, submitted to

Earth Planet. Sci. Lett., *223*, 35-48, 2004.
Wang, K., J. F. Cassidy, I. Wada, and A. J. Smith, Effects of metamorphic crustal densification on earthquake size in warm slabs, *Geophys. Res. Lett., 31*, L01605, doi:10.1029/2003GL018644, 2004a.
Wang, K., I. Wada, and Y. Ishikawa, Qualitative analyses of stresses in the subducting slab beneath Southwest Japan, *J. Geophys. Res*., *109*, B08304, doi:10.1029/2003JB002888, 2004b.